REDUCING HEAT STRAIN USING PHASE-CHANGE COOLING VESTS WITH DIFFERENT MELTING TEMPERATURES

Jim House, Heather Lunt*, Rowan Taylor, Carol House, Jason Lyons and Gemma Milligan**

Institute of Naval Medicine, Alverstoke, Gosport, PO12 2LJ, UK
**Department of Sport & Exercise Science, University of Portsmouth, PO1 2ER, UK*

Contact person: jim.house@port.ac.uk

INTRODUCTION

Many types of personal cooling equipment are available for those experiencing heat strain. A relatively simple cooling device is a cooling vest (CV) in which a frozen substance (usually sealed within bags) is placed within pockets of a cooling waistcoat. Traditionally, ice, or a frozen water based solution, is used as the coolant, and thus the 'ice-vest' melts at 0°C (CV_0). If a CV_0 contained 1kg of ice at minus 18°C and was worn until the ice had melted and the water temperature increased to 20°C, then it would absorb 456kJ of heat, (calculated from the specific heat capacity of ice, water and the latent heat of fusion of water). Sixty-four percent of the heat absorbed in this process (334kJ) occurs as the ice melts and 36% of the heat energy (122kJ) is absorbed due to the 38°C increase in temperature.

In recent years other substances have been used as coolants in CVs, such as long-chain alkanes (*e.g.* hexa- and tetra-decane). These compounds are frozen and provide the majority of their cooling benefit, like ice, at the point at which they melt. The main advantage of an alkane-based CV (CV_A) is that, if it melts at 20°C, then it can be re-frozen by cooling below 20°C and thus a freezer is not required. Another reported advantage is that a substance which melts at 20°C may cause less peripheral vasoconstriction than a CV_0. This advantage is widely reported by manufacturers of CV_A systems as contributing to a greater cooling power compared to a CV_0, although no evidence has been cited in support of this.

Although it might be expected that vasoconstriction would occur when the skin is cooled by contact with ice, this might not occur when hyperthermic; The maintenance of skin blood flow despite local skin cooling is the basis of an efficient conductive cooling technique, although even without good skin blood flow a conductive pathway through the tissues will eventually be established with prolonged cooling. Accordingly, there may be no physiological advantage to wearing CV_A in place of a CV_0. Indeed, as the latent heat of fusion and the specific heat capacity of long-chain alkane compounds are lower than those of water/ice the combined physical cooling power of a CV_A may be reduced by 40 % to 45 % per kg compared to a CV_0 of the same mass. This study was conducted to measure the cooling effect of four CV which melt at 0°C, 10°C, 20°C and 30°C compared to a no-cooling control condition (control).

It was hypothesised that none of the cooling vests would cause vasoconstriction, and subsequently that the CV_0 would afford the greatest physiological cooling benefit, having the greatest physical cooling capacity per kg of coolant compared to CV_A.

METHODS

The protocol was approved by the Ministry of Defence (Navy) Personnel Research Ethics Committee. On each of five different days, ten medically-fit volunteer participants, who had given their written informed consent, undertook a light stepping exercise (12 $steps.min^{-1}$, 22.5 cm) for 45 minutes, and then rested for 45 minutes. The experiment was conducted in a controlled climate (40°C dry bulb, 29.5 °C wet bulb) and the participants wore fire-fighting clothing over polyester/cotton work trousers and a cotton T-shirt. The participants undertook the five conditions, each on a different day in a balanced randomised order to assess the different CV types (CV_0, CV_{10}, CV_{20} and CV_{30}) with a mass of 2.4kg and initially frozen to minus 18°C.

Rectal temperature (T_{re}) was monitored using a thermistor self-inserted to 15 cm beyond the anal sphincter. Mean skin temperature (T_{msk}) was estimated from skin temperature (T_{sk}) recorded by four thermistors, at the shin, thigh, upper arm and chest according to Ramanathan (1964). Mean body temperature (T_b) was calculated from $0.8T_{re} + 0.2T_{msk}$ (Colin *et al.*, 1971). Body cooling power was calculated from body mass and changes in T_b and an assumed body specific heat capacity of 3.47 $kJ.kg^{-1}$. Heart rate (HR) was monitored continuously using a 3-lead electrocardiogram (Diascope, SW Vickers, UK). Skin blood flow (SkBF) was estimated using laser Doppler flowmetry (LDF) (MoorLab, Moor Instruments Ltd, UK) recorded digitally (PowerLab, ADInstruments Ltd, UK). In each experiment a LDF probe was attached to the left chest of each subject adjacent to the chest T_{sk} thermistor, but ensuring that its position was underneath one of the CV cooling packs (where worn). Subjects were also requested to report their order of preference for the five conditions.

RESULTS

Figure 1 shows the change in T_{re} during the exercise and resting recovery period.

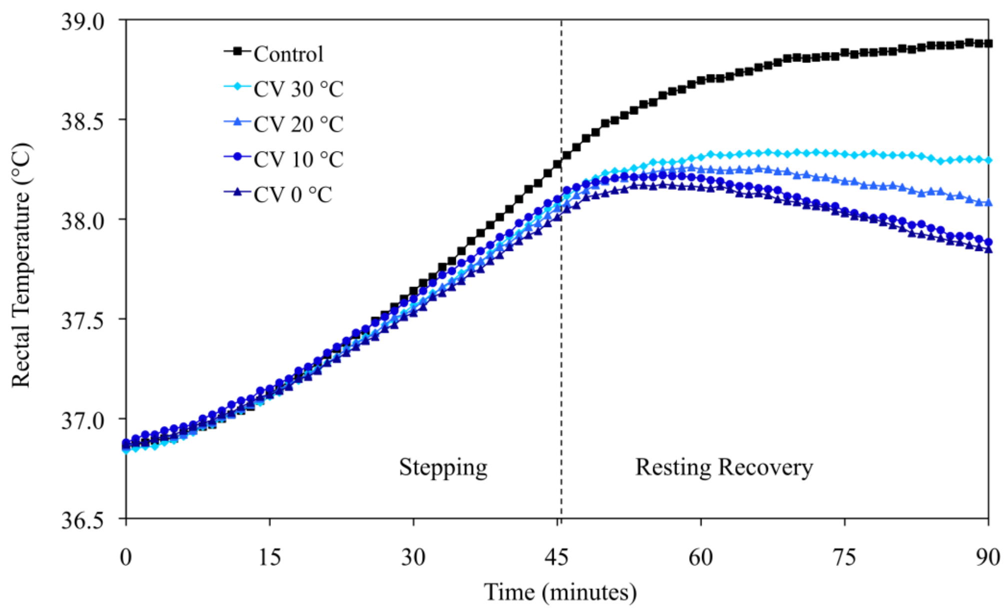

Figure 1. Mean rectal temperature when wearing different cooling vests whilst stepping and during resting recovery (*n*=10).

At the end of the experiment all vest types had mostly, or completely, melted. Repeated measures analysis of variance (ANOVA) showed that at the end of the work period T_{re} was lower in the CV_0 condition compared to the control (P<0.05). T_{re} for the other cooling vests (CV_{30}, CV_{20} and CV_{10}) was intermediated to the CV_0 and control conditions, and not significantly different from either, although there was a tendency for the vests to be closer to the CV_0 condition than the control (P<0.07). Following recovery T_{re} was lower for all vest conditions compared to the control (P<0.05). Additionally, T_{re} was lower in the CV_0, CV_{10}, and CV_{20} conditions compared to the CV_{30} (P<0.05).

During exercise T_b rose at similar rates in the CON, CV_{30} and CV_{20} conditions, but this rise was attenuated in the CV_{10} and CV_0 conditions (P<0.05). During resting recovery the rate of change of T_b was lower in all vest conditions compared to CON (P<0.05). Also, T_b fell at a faster rate in CV_{10} and CV_0 compared to CV_{30} and CV_{20} (P<0.01). Differences in the change of body heat storage between the vest and control conditions show that the CV_{10} provided 29W of cooling during stepping, and the CV_0 40W of cooling. During the rest periods the vests afforded cooling benefits of 29W (CV_{30}), 55W (CV_{20}), 66W (CV_{10}) and 69W (CV_0). The CV_0 and CV_{10} conditions attenuated the rise in heat storage and cooled more during recovery than the CV_{20} and CV_{30} conditions (P<0.05).

Figure 2 shows SkBF during the exercise and recovery periods.

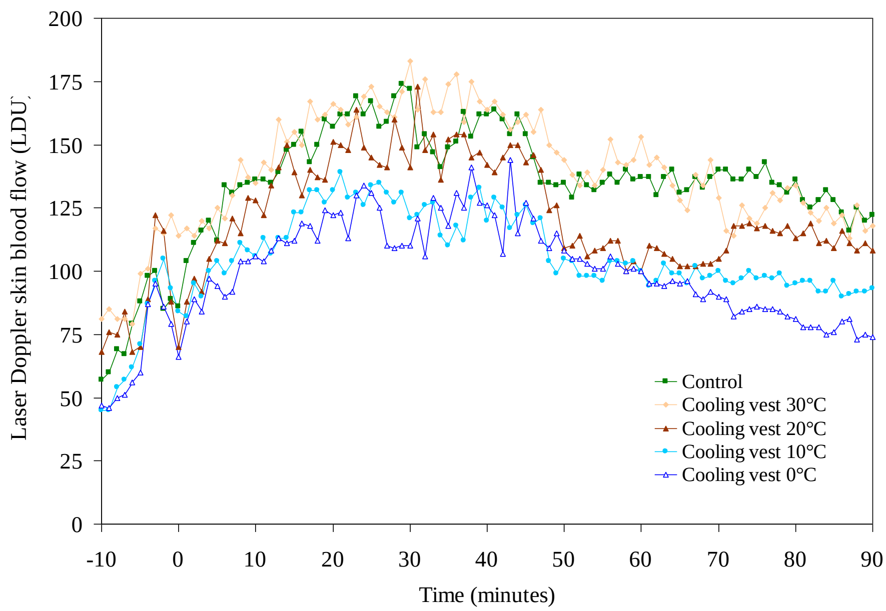

Figure 2. Mean abdomen laser Doppler skin blood flow when wearing different cooling vests (n=10).

There were no significant differences in SkBF 10 minutes pre-exercise prior to the cooling vests being donned. There was obvious disruption to SkBF in the 5 minutes prior to exercise as the vests were donned. At the start of exercise, SkBF was not significantly different in any of the vest conditions compared to the control. In all conditions, SkBF was greater at the end of the work period compared to the start (P<0.05), and lower at the end of rest compared to the start of recovery (P<0.05). There were no significant differences in SkBF across conditions detected at any time.

HR was similar between conditions at the start of the exercise period. At the end of the stepping exercise HR was lower in the CV_{20} and CV_0 conditions compared to the control ($P<0.05$), with an indication that HR was also lower in the CV_{10} ($P<0.06$). HR was not reduced when wearing the CV_{30}. After 5 minutes of recovery, and throughout the remainder of the rest period, HR was lower in all vest conditions compared to the control ($P<0.05$). After 15 minutes of rest, and thereafter, HR was lower in CV_0 compared to CV_{30}. After 25 minutes of rest, and thereafter HR, was lower in the CV_0 compared to the CV_{20}. At the end of the rest period, HR was lower in the CV_0 compared to all other vest conditions.

Subjectively, all vests were preferred to the control ($P<0.005$), and the CV_{10} was the preferred vest ($P<0.001$). Subjects reported that the CV_0 was "too cold", and in this condition cold-induced erythema was commonly observed.

CONCLUSIONS

The data presented support our hypotheses, that no vasoconstriction occurred on donning any types of the cooling vests, and that the CV_0 afforded greater physiological cooling than the other CV_A. However, the physiological cooling benefits attained wearing the CV_{10} was closer to that of the CV_0 than to the CV_{20} and CV_{30}. As subjects reported that the CV_0 felt too cold, and that erythema was observed at the end of this condition, it would seem preferable to use the CV_{10} rather than the CV_0.

Calculations using the thermophysical properties of the coolants show that the CV_0 has the greatest cooling potential (1194kJ) compared to the CV_{10} (732kJ), CV_{20} (753kJ) and CV_{30} (789kJ), if the vests were initially frozen to minus 18°C and increased in temperature to 30°C. Why CV_0 and CV_{10} afford similar cooling powers distinct from that of the CV_{20} and CV_{30} must be due to other factors, such as cooling gradients and SkBF. Cooling will occur by direct conduction through the tissues and also by mass transfer through the circulation; although no statistically significant differences in SkBF were detected between conditions, possibly because of the inherent variability of SkBF. Figure 2 indicates that SkBF throughout the experiment may have been generally lower with a lower vest melting temperature. However, even if SkBF was actually lower with the colder vests, and thus mass transfer cooling reduced, a compensatory increase of conductive tissue cooling was likely due to the greater cooling gradient between skin and core temperatures.

In summary, the greatest cooling power occurred with cooling vests melting at 0°C and 10°C with a subjective preference for 10°C as 0°C was perceived as too cold.

ACKNOWLEDGEMENTS

We gratefully acknowledge the assistance of the ten participants who freely gave up their time, and thermal comfort to participate in this study. We also acknowledge the staff at the Institute of Naval Medicine for their kind assistance, particularly Dr Dan Roiz de Sa for acting as Independent Medical Officer for this study, and Mr David Grist and Mrs Sue Wade for providing medical supervision during the study. Dr Shaun Kilminster for providing statistical support. Dr

Adrian Allsopp, Head of the Environmental Medicine Unit for review and kind permission to publish this study.

REFERENCES

Colin, J., Timbal, J., Houdas, Y., Boutelier, C. & Guieu, J.D. 1971. Computation of mean body temperature from rectal and skin temperatures. *J. Appl. Physiol.* 31(3), 484-489.

Ramanathan, N.L. 1964. A new weighting system for mean surface temperature of the human body. *J. Appl. Physiol.* 19(3), 531-533.